GEOTECHNICAL CHARACTERIZATION AND EVALUATION OF SITE AMPLIFICATION AT SELECTED PNSN STRONG MOTION SITES, SEATTLE, WASHINGTON

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PROGRESS REPORT – YEAR 2
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In order to accurately quantify the earthquake ground-shaking hazard in the Seattle metropolitan area and surrounding Puget Sound region, the effects of unconsolidated and semiconsolidated sedimentary and glacial deposits on ground motion need to be evaluated. This project is a continuation of our efforts to evaluate the near-surface site amplification of earthquake ground motions in the Puget Sound region. In a 1997-1998 NEHRP-funded study, we collected geologic, geophysical, and geotechnical data necessary to characterize the near-surface geology of the Seattle metropolitan area (Wong *et al.*, 1999a; 1999b). Additional V_S measurements at 9 selected sites were performed using the Spectral-Analysis-of-Surface-Wave (SASW) technique and added to the existing database. In a 2000-2001 NEHRP-funded study, we digitized the V_S database as well as augmented it with a small amount of data made available through efforts associated with Project Impact (Wong *et al.*, 2003). Midway through this current study, the moment magnitude (**M**) 6.8 Nisqually earthquake occurred on 28 February 2001 providing a unique dataset of strong motion records. Preliminary analysis of these data indicates that site amplification effects were significant at the strong motion recording sites.

Objectives

In this two-year funded study, the major goals were to measure the V_S profiles using SASW at 25 to 30 Pacific Northwest Seismograph Network (PNSN) strong motion sites that recorded the 2001

earthquake and evaluate the near-surface site amplification at these stations. The study will accomplish three important objectives: (1) provide critical geotechnical data for characterizing the site geology at these strong motion sites; (2) improve our V_S database; and (3) evaluate and characterize the site response effects on the recorded Nisqually earthquake ground motions.

In this study we hope to define and characterize distinct geologic site response categories in the Seattle area, which will vary as a function of thickness above a defined reference rock (or stiff linear behavior material) datum. This characterization will be based on the analysis of the Nisqually data as well as an analysis of the borehole and cross-section data collected in the previous studies and with information now being compiled as part of the Seattle Area Geologic Mapping Project. Based on these site categories, near-surface amplification factors can be computed as a function of the level of input motion at the reference datum. This characterization of near-surface amplification will be made available to the USGS for their possible use in the development of microzonation hazard maps of the Seattle metropolitan area.

Scope of Work

The project is divided into three tasks: (1) perform SASW surveys at 30 PNSN strong motion sites with the University of Texas at Austin in Year 1; (2) evaluate site amplification; and (3) prepare the final report and disseminate results. Tasks 2 and 3 were originally scheduled to be performed in Year 2.

Because of a delay in completing production of the University of Texas truck-mounted vibrator that is being funded by a NSF-NEES grant, the SASW surveys were not performed in Year 1. However, the vibrator was manufactured, tested, and prepared for deployment such that the surveys were performed at the beginning of Year 2. We selected 30+ strong motion sites where the SASW surveys were to be performed. The stations included both Advanced National Seismic System (ANSS) stations operated by the University of Washington and National Strong Motion Program (NSMP) stations operated by the USGS (Table 1). The majority of the sites are located in the Seattle metropolitan area but also include stations in Bremerton, Olympia, and Puyallup. The near-surface geology of the Puget Sound region is dominated by a complex interbedded and discontinuous sequence of glacial and nonglacial deposits. Thus most of the surveyed strong motion sites are underlain by glacial till with the remaining sites on Holocene alluvium, glacial recessional and advance outwash deposits, or manmade fill/modified land. Initial visits were made to all but two sites to select survey locations. Permission was received from landowners and property managers to perform the surveys.

Results

From 12-21 November 2003, a total of 33 sites were surveyed including a site of a deep USGS borehole in Volunteer Park (Table 1 and Figure 1). Surveys reached depths ranging from 100 to 290 ft. The SASW data were analyzed by the Dr. Ken Stokoe and his students and V_S profiles estimated. An example profile is shown on Figure 2.

The 32 strong motion sites were classified by NEHRP categories based on the SASW results (Table 1). A preliminary analysis of the NEHRP categories, SASW data, and the peak horizontal accelerations was performed and presented at the 2004 Seismological Society of America Annual Meeting in Palm Springs (Wong *et al.*, 2004).

Ground motions in the 2001 Nisqually earthquake recorded at the 32 sites, as characterized by peak horizontal ground acceleration (pga), ranged from 0.04 to 0.31 g. Two sites, SEW and SP2, 800 m apart in Seward Park, Seattle, at an epicentral distance of about 60 km, recorded pga values of 0.17 and 0.31 g (Table 1). Both sites are underlain by soil atop till. In contrast, the closest station to the earthquake (distance of ~ 17 km) is underlain by recessional deposits and recorded a maximum pga of only 0.07 g. In general, ground motions were highest at sites underlain by lower velocity materials (e.g., alluvium, outwash) relative to stiffer sites such as the glacial till. Apparently the ground motions at moderate to high frequencies (2 to 10 Hz) are strongly affected by near-surface geology and this is exemplified by the two Seward Park sites.

A request for a one-year no-cost time extension of the grant was made and approved. The end date of the grant is now 31 October 2005. The next step in the project is to analyze the 2001 Nisqually data for near-surface site amplifications. Based on the V_S profiles, a RVT-based equivalent-linear site response methodology will be used to compute the amplification at the strong motion sites and compare the predicted transfer functions against the observed transfer functions.

Non-Technical Summary

The 28 February 2001 **M** 6.8 Nisqually earthquake was recorded by more than 70 strong motion sites within the Pacific Northwest Seismic Network (PNSN) and National Strong Motion Program (NSMP). To evaluate the effects of the shallow soils on the recorded Nisqually ground motions, we have characterized the shear-wave velocity (V_S) structure to depths of 30 to 100 m at 33 sites around the Puget Sound using the Spectral-Analysis-of-Surface-Waves (SASW) technique. These data will be used to numerically model ground motions the 2001 ground motions and compare the predictions with the actual recordings of the 2001 earthquake. This evaluation will help improve our understanding of site response effects in the Seattle area.

Publications

Wong, I.G., Cox, B., Menq, F-Y, Lin, Y-C, and Stokoe, K.H., II, 2004, V_S surveys of strong motion sites in the Puget Sound region, Washington, and preliminary analysis of shallow site response in the 2001 **M** 6.8 Nisqually earthquake (abs.), Seismological Research Letters, v. 75, p. 248.

Wong, I.G., Sparks, A., Metcalfe, R., Wright, D.H., Kalinski, M.E., Stokoe, K.H., Brown, L.T., and Yount, J.C., 1999a, Geologic/geophysical database to characterize site response in the Seattle, Washington metropolitan area (abs.), Seismological Research Letters, v. 70, p. 256.

Wong, I., Sparks, A., Metcalfe, B., Wright, D., Stokoe, K., and Yount, J., 1999b, Probabilistic seismic hazard analysis and ground shaking microzonation maps for the Seattle, Washington, metropolitan area: Characterization of the near-surface geology (Year 1), unpublished Final Technical Report submitted to the U.S. Geological Survey, USGS Award No. 1434-HQ-97-GR-03024.

Wong, I., Sparks, A., Thomas, P., and Nemser, E., 2003, Evaluation of near-surface site amplification in the Seattle, Washington, metropolitan area, Final Technical Report submitted to the U.S. Geological Survey, USGS Award No. 00HQGR019.

Table 1
Puget Sound Strong Motion Sites Recording the 2001 Nisqually Earthquake

Station	Location	Surficial Geology	Hypocentral Distance (km)	Recorded PGA(g)	V_S 30	NEHRP Site Class	Comments
MURR	Camp Murray, Tillicum	Qvr	54	0.07	1904	C	Rock at 145 ft
7008	Halvorsen Residence, Olympia	Qdvt	54	0.16	1131	D	
2101	Highway Test Lab, Olympia	Qal	55	0.22	623	D/E	
UPS	University of Puget Sound, Tacoma	Qvt	56	0.06	1705	C	Rock at 140 ft
PCFR	Pierce County Training Center, Roy	Qvt	59	0.13	1617	C	
PCEP	Pierce County East Precinct, Puyallup	Qvr	62	0.21	1445	C	Rock at 195 ft
KIMR	Kitsap County Airport, Bremerton	Qvr	66	0.16	1937	C	Rock at 180 ft
PCMD	Pierce County Mountain Detachment, Eatonville	Qvt	67	0.16	1802	C	
7030	SEATAC Fire Station	ml	69	0.19	1242	C/D	Rock at 170 ft
7034	Bremerton Fire Station	Qdvt	69	0.19	1849	C	Rock at 140 ft; 40 ft soil over till?
GNW	Tahyua Lake, Bremerton	Intrusive rock	70	0.16	3318	B	Rock at 30 ft
RBEN	Benson Hill School, Renton	Qvt	74	0.11	1602	C	
HOLY	Holy Rosary School, West Seattle	Qvt	74	0.10	1263	C/D	
MPL	Maple Valley Substation, Renton	Qvt	75	0.10	1462	C	Rock at 155 ft
7032	West Seattle Fire Station #29	Qva	75	0.15	1144	C/D	Deep soil
7027	Seattle Fire Station #28	Tb	75	0.08	2915	B	Rock at 25 ft
SEW	Seward Park, Seattle	Rock (Blakeley Fm)	77	0.17	2056	C	Rock at 60 ft
KIMB	Kimball School, Beacon Hill, Seattle	Qvt	77	0.17	1776	C	
SP2	Seward Park, Seattle	Qvt	78	0.31	1304	C	Rock at 100 ft
RHAZ	Hazelwood School, Renton	Qvt	79	0.05	2492	B/C	Rock at 80 ft

Table 1 (continued)
Puget Sound Strong Motion Sites Recording the 2001 Nisqually Earthquake

QAW	Queen Anne Hill, Seattle	Qva	80	0.11	1413	C	Low V_S zone
LAWT	Lawton School, Magnolia, Seattle	Qva	81	0.10	1176	C/D	
RAW	Raver BPA Substation	Qvr	82	0.17	1374	C	Rock at 120 ft
SEA	ATM Building, UW	Qvt	83	0.07	1587	C	
WISC	Wilburton Center, Bellevue	Qvt	84	0.11	2228	C	Rock at 40 ft
NOWS	NOAA Sand Point, Seattle	ml	87	0.09	931	D	Deep soil
BRKS	Brookside School, Bothell	Qal	91	0.10	619	D/E	Till at 100 ft?
ELW	Echo Lake BPA Station	Qmw	91	0.06	1720	C	Rock at 80 ft; till at 30 ft?
ALCT	Alcott School, Redmond	Qvr	92	0.04	1390	C	Stiff soil, nearly constant V_S
LEOT	Leota School, N. of Lake Leota	Qvt	98	0.08	1479	C	
EARN	East Ridge School, Redmond	Qvr	99	0.07	1801	C	15 ft soil over till?
MBPA	Monroe BPA Substation	ml	117	0.15	1460	C	Rock at 85 ft

Qvt Vashon till
Qvr Vashon recessional outwash
Qva Vashon advance outwash (Esperance sand)
Qal Holocene river alluvium
ml Modified land
Tb Blakeley Formation (rock)

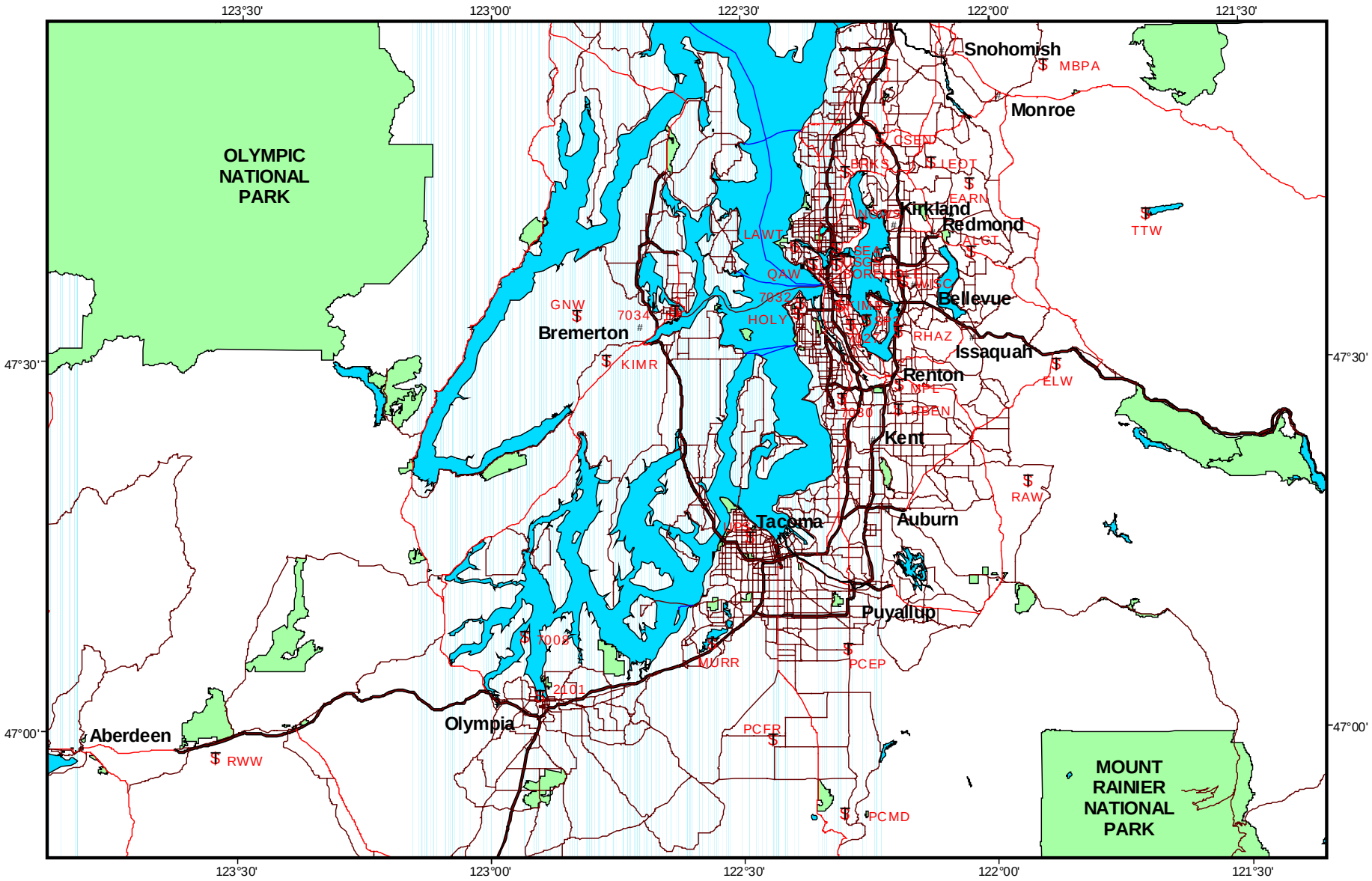
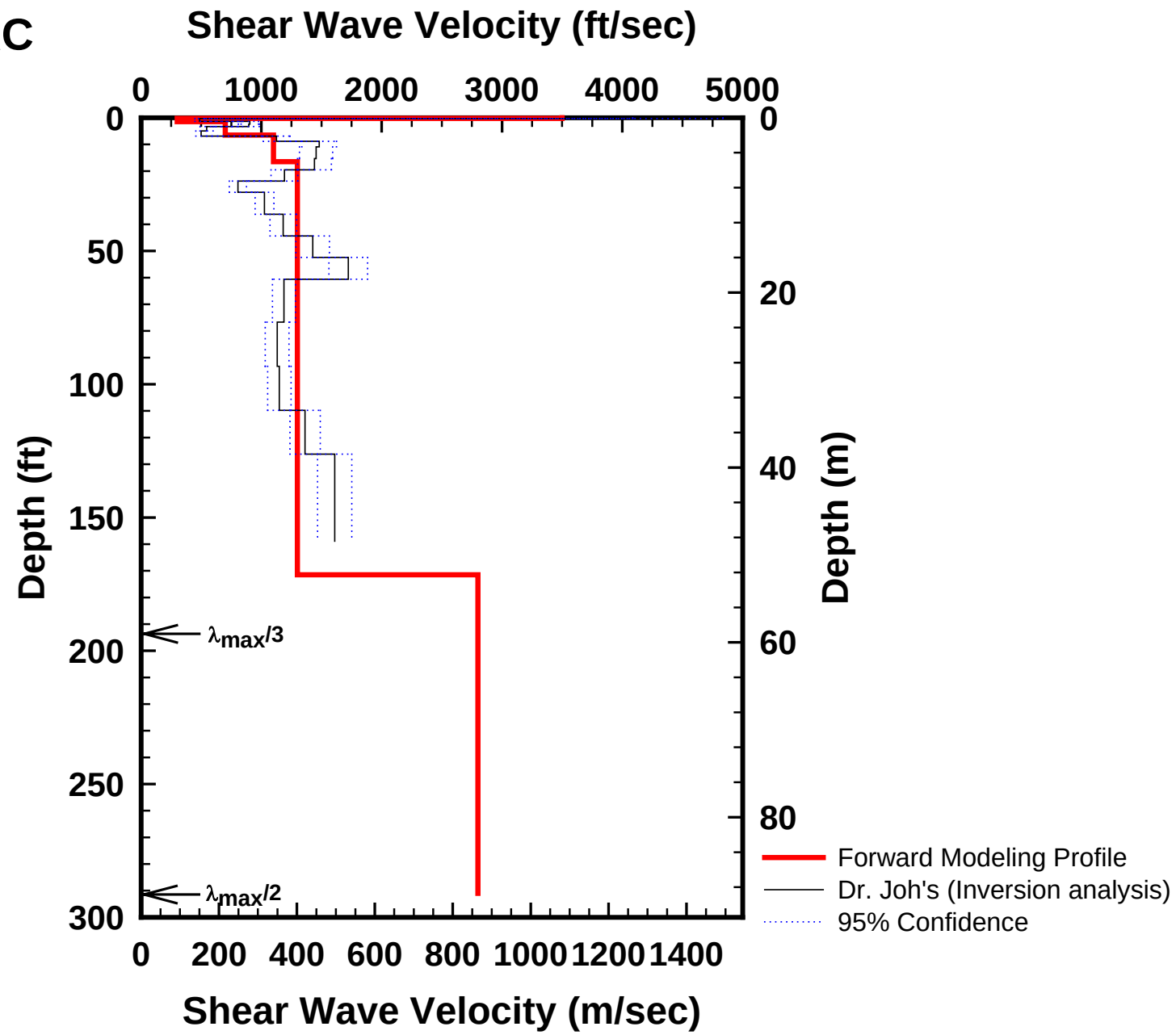


Figure 1. Surveyed Strong Motion Sites

SEATAC


Shear Wave Velocity (ft/sec)
0
1000
2000
3000
4000
5000
Depth (ft)
0
50
100
150
200
250
300
λmax/3
λmax/2
Depth (m)
0
20
40
60
80
0
200
400
600
800
1000
1200
1400
Shear Wave Velocity (m/sec)
Forward Modeling Profile
Dr. Joh's (Inversion analysis)
95% Confidence